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Heat fluctuations in an out of equilibrium bath

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We measure the energy fluctuations of a Brownian particle confined by an optical trap in an aging gelatin after a very fast quench (less than 1 ms). The strong nonequilibrium fluctuations due to the assemblage of the gel, are interpreted, within the framework of fluctuation theorem, as a heat flux from the particle towards the bath. We derive, from a simple model, an analytical expression of the heat probability distribution, which fits the experimental data and satisfies a fluctuation relation similar to that of a system in contact with two baths at different temperatures.

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The heat flux between two reservoirs at different temperatures is an important and useful example of an out of equilibrium process. In small systems this heat flux is a strongly fluctuating quantity and the probability distribution of these fluctuations has been recently widely studied, within the context of fluctuation theorems [1]. These studies have been mainly devoted to the steady state, that is when the temperatures T_A and T_B of the two reservoirs, A and B , are kept constant. In such a case the probability distribution $P(Q_\tau)$ of exchanging with the reservoir A the heat Q_τ in a time τ , is related to the that of exchanging the quantity $-Q_\tau$ according:

$$\ln \frac{P(Q_\tau)}{P(-Q_\tau)} = \Delta\beta Q_\tau \quad (1)$$

where $\Delta\beta = (1/T_B - 1/T_A)/k_B$, k_B is the Boltzmann constant and $k_B\Delta\beta Q_\tau$ can be easily identified as the entropy production during the time τ [1–3]. This equation has been derived for several theoretical models [3, 4] in the stationary regime. However the non stationary case, although very useful for applications, has been studied only in some specific models [5] of systems relaxing towards equilibrium. Thus one may wonder whether a relation like Eq. (1) may still hold, how it is eventually modified and what kind of information on the system can be obtained [5].

These important questions have never been analyzed in any experiment. Thus the purpose of this letter is to give new insight to this problem, by measuring the energy fluctuations of a Brownian particle used as a probe inside a gelatin relaxing towards its solid-like state (gel), after a very fast quench, from above to below the gelation temperature T_{gel} . The main result of our investigation is that these fluctuations can be interpreted as a heat flux from the particle towards the bath. The measured $P(Q_\tau)$ satisfies an equation formally equivalent to Eq. (1), but in this case $\Delta\beta$ is a decreasing function of time. The $P(Q_\tau)$ can be fitted by an analytical expression that we derive from a Langevin equation for a Brownian particle coupled with an out of equilibrium bath.

The experiment has been performed using gelatin, a

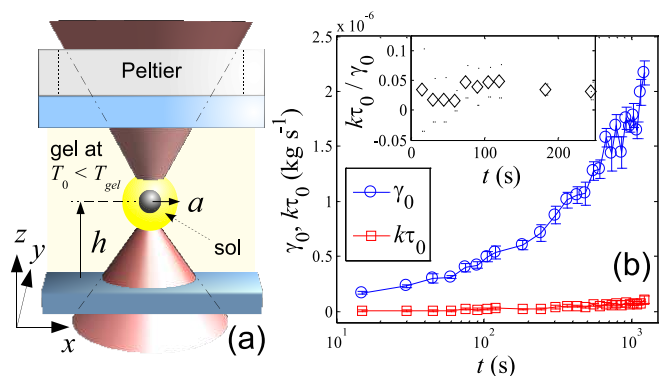


FIG. 1. (a) Schematic representation of the experimental setup to perform a local quench in a sol droplet around a trapped particle in the gel bulk. (b) Time evolution of the viscous drag coefficient γ_0 of the particle and the correlation time τ_0 of the gelatin droplet measured after the quench at $f = 5$ Hz. Inset: $k\tau_0/\gamma_0$ as a function of time.

thermoreversible gel obtained from denatured collagen. Above T_{gel} an aqueous gelatin solution is in a liquid viscous phase (sol), whereas below T_{gel} the formation of a network of cross-linked filaments leads to an elastic solid-like phase (gel) [6]. In this gel phase the gelatin viscoelastic properties slowly evolve toward equilibrium and share some common phenomenological features with glassy dynamics [7–9]. We are interested in this transient out-of-equilibrium regime, that we use to study the fluctuations of the energy fluxes from and to the heat bath in the nonstationary case. A similar problem has been theoretically analyzed for the first time in Ref. [5] for a model of aging spin glasses. It has been found that a relation like Eq. (1) can be applied to a relaxing system to obtain quantitative informations on the heat exchanges with the bath. We show in this letter that this approach, exploited only once in real experiments [10], can be indeed very useful for understanding the properties of a Brownian particle in an out-of-equilibrium bath.

In the present experiment, an aqueous gelatin solution

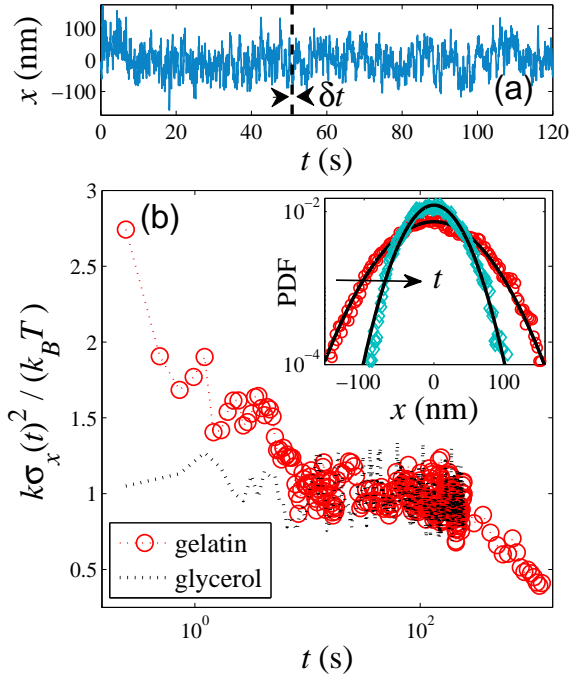


FIG. 2. (a) Time evolution of x after a quench. $\sigma_x(t)^2$ is computed over $\delta t = 0.1$ s and over 60 independent quenches. (b) Time evolution of $\sigma_x(t)^2$ (normalized by $k_B T/k$) after the quenches performed in gelatin (o) and glycerol (dashed line). Inset: Probability density of x at $t = 0.5$ s and 50 s for the quench in gelatin. The solid lines are Gaussian fits.

(type-B pig skin) at a concentration of 10%wt is prepared following the usual protocol [9]. For this sample $T_{gel} = 29^\circ\text{C}$. This solution fills a transparent cell the temperature of which is controlled by a Peltier element [Fig. 1(a)], at $T_0 = 26 \pm 0.05^\circ\text{C} < T_{gel}$. Thus the solution inside the cell is in the solid-like phase. A silica bead, of radius $r = 1 \mu\text{m}$, is kept inside the gelatin in the focal position of a tightly focused laser beam ($\lambda = 980$ nm) at a power of 20 mW. At this power the laser produces on the particle an elastic force of stiffness $k = 2.9$ pN/ μm . Because of light absorption, the temperature of the trapped particle is $T = 27^\circ\text{C}$, which is still smaller than T_{gel} . Therefore the bead is inside the solid gel in the beam focus at a distance $h = 25 \mu\text{m}$ from the cell wall, see Fig. 1(a) [11]. Starting from this condition, the laser power is increased to 200 mW and the local temperature around the focus rises to $38^\circ\text{C} > T_{gel}$. As a result the gel melts and a liquid droplet of radius $a = 5 \mu\text{m}$, is formed around the trapped bead inside the solid gel bulk, as sketched in Fig. 1(a). After 180 s, the laser power is suddenly decreased again to 20 mW so that the temperature is homogenized by heat diffusion into the bulk in less than 1 ms resulting in a very efficient quench of the droplet to the final temperature $T < T_{gel}$. At T the liquid inside the droplet solidifies in about 1 hour

and the particle, trapped in the center of the drop by the focused beam, is a probe of this relaxation dynamics. The quenching procedure is repeated 60 times in order to perform the proper ensemble averages.

Immediately after the quench we record the time evolution of the x position [see Fig. 1(a)] of the trapped particle measured by a position sensitive detector whose output is sampled at 8 kHz and acquired by a computer. The resolution of the measurement of x is about 1 nm [10, 12]. In order to characterize the particle dynamics we measure, using active microrheology [10], the time evolution of the viscous drag coefficient γ_0 of the particle and the largest correlation time τ_0 of the fluid. This is done by measuring the response of the bead at a time-dependent sinusoidal force F of amplitude 87 fN and frequency f applied to the bead. The force $F = kx_0$ is obtained through the modulation of the beam focus position x_0 . The results for γ_0 and $k\tau_0$, measured at $f = 5$ Hz, are shown in Fig. 1(b). First, for $t \lesssim 200$ s after the quench there is a transient regime where the droplet is purely viscous, $\tau_0 \simeq 0$, whereas γ_0 increases in time. In this regime γ_0 and τ_0 do not depend on f . For $t > 200$ s the liquid gelatine inside the drop has a behavior similar to that observed in macroscopic samples [6, 9], *i.e.* the liquid drop is actually undergoing gelation. We will study the nonequilibrium statistical properties of the bead dynamics in the very first 200 s after the quench where the liquid gelatin inside the drop is mainly viscous and the elasticity is negligible with respect to k , as shown in the inset of 1(b), where we plot $k\tau_0/\gamma_0$ as a function of time.

We begin by analyzing the variance $\sigma_x(t)^2$ of x at time t after the quench. $\sigma_x(t)^2$ is computed over 60 independent quenches and over a short time window $\delta t = 0.1$ s around each value of t in order to improve the statistics, as depicted in Fig. 2(a). The time evolution of $\sigma_x(t)^2$ is plotted in Fig. 2(b). At the beginning, $\sigma_x(t)^2$ is almost three times the equipartition value $k_B T/k$ that would be obtained at equilibrium. This shows the presence of a stochastic force on the particle due to the transient formation of the gel network. This force weakens compared to the thermal fluctuations becoming negligible at ~ 20 s so that $\sigma_x(t)^2$ slowly decreases in time, reaching the equilibrium value for $t \gtrsim 20$ s. This relaxation timescale is two orders of magnitude larger than the initial viscous relaxation time of the particle: $\tau_k = \gamma_0/k = 65$ ms. Finally for $t \gtrsim 200$ s, $\sigma_x(t)^2$ starts again to decrease because of the appearance of a strong elastic component of the gel confirming the direct measure of γ_0, τ_0 , shown in Fig. 1(b), and justifying that for $t \leq 200$ s the gelatin elasticity is negligible. During this relaxation process x remains Gaussian as shown in the inset of Fig. 2(b).

In Fig. 2(b) we also plot the time evolution of $\sigma_x(t)^2$ measured, after the same quenching procedure, in a Newtonian fluid (glycerol 60%wt in water) with the same viscosity of the initial sol phase of gelatin. In this case, the particle dynamics must settle into an equilibrium state in

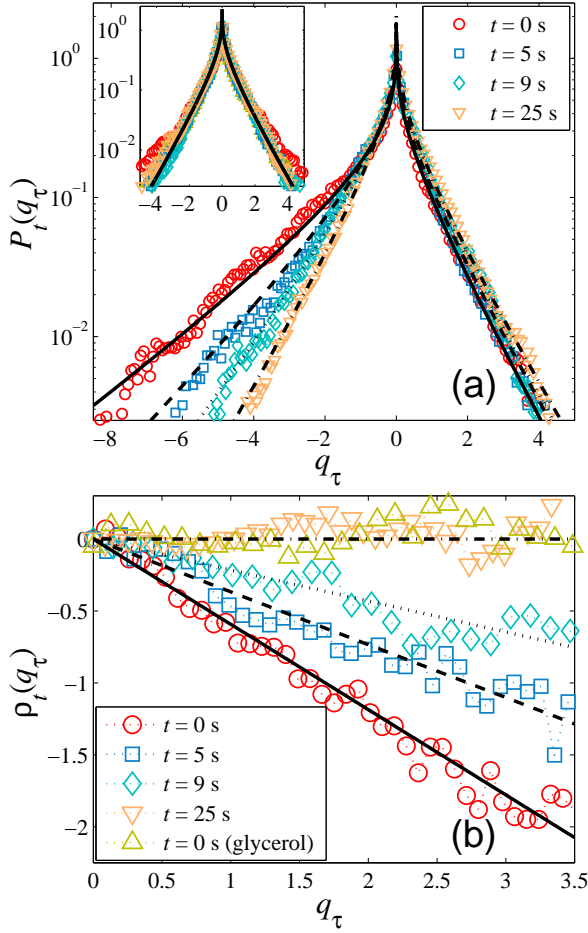


FIG. 3. (a) Probability density $P_t(q_\tau)$ of the normalized heat $q_{t,\tau}$ for $\tau = 30$ s at different times t after the quench. The theoretical lines are computed using Eq. (5). Inset: $P_t(q_\tau)$ computed, at the same t and τ during a quench performed in glycerol. The solid line corresponds to the theoretical equilibrium profile. (b) Asymmetry function of the $P_t(q_\tau)$ shown in (a). The straight lines are obtained using Eq. (6).

a time $\sim \tau_k$ after the quench [13]. Indeed in Fig. 2(b) we see that, in glycerol, $\sigma_x(t)^2 = k_B T/k$ for all t within the experimental accuracy. This confirms that no experimental artifact is present and that the observed dependence of $\sigma_x(t)^2$ in gelatin is a real non-equilibrium effect due to the sol-gel transition.

We now focus on the energy fluctuations of the particle inside the droplet for $t < 200$ s, *i.e.* when $k\tau_0/\gamma_0 \ll 1$. Thus the energy of the particle is simply $U(t) = kx(t)^2/2$. As there is no external force acting to the particle, the energy fluctuation $\Delta U_{t,\tau}$ during the time τ is equal to the heat $Q_{t,\tau}$ exchanged between the particle and the bath [14], specifically

$$Q_{t,\tau} = \Delta U_{t,\tau} = \frac{k}{2}(x_{t+\tau}^2 - x_t^2). \quad (2)$$

The mean heat transferred during $[t, t + \tau]$ is

$\langle Q_{t,\tau} \rangle = (k/2)[\sigma_x(t+\tau)^2 - \sigma_x(t)^2] \leq 0$, which reveals the existence of a mean heat flux from the particle to the surroundings over the timescale τ because of the relaxation of σ_x . The maximum value $|\langle Q_{t,\tau} \rangle| \approx k_B T$ takes place at $t = 0$ s and for $20 \text{ s} \lesssim \tau \lesssim 200$ s. Non-negligible values of the mean heat compared to $k_B T$ persist for several seconds after the quench. Nevertheless, as t increases, $|\langle Q_{t,\tau} \rangle|$ decreases becoming negligible and experimentally undetectable for $t \gtrsim 20$ s.

The probability density function $P_t(q_\tau)$ of the normalized heat $q_{t,\tau} = Q_{t,\tau}/(k_B T)$ is computed over the 60 quenches and over a short time window $\delta t = 0.1$ s around each t and $t + \tau$, as sketched in Fig 2(a). We focus on a large value of τ in order to probe timescales comparable to the relaxation of the nonthermal fluctuations. Fig. 3(a) shows $P_t(q_\tau)$ at different times t after the quench for $\tau = 30$ s. $P_t(q_\tau)$ is highly non-Gaussian with a spike at $q_\tau = 0$ and slowly decaying tails for all the values of t . Immediately after the quench, $P_t(q_\tau)$ is strongly asymmetric with a long tail occurring at negative fluctuations. As t increases this asymmetry decreases and $P_t(q_\tau)$ becomes symmetric at $t \gtrsim 20$ s. Once again, we check that the long-lived asymmetry occurs because of the intricate nonequilibrium nature of the bath. In the inset of Fig. 3(a) we plot $P_t(q_\tau)$ with $\tau = 30$ s for the local quenches performed in glycerol. $P_t(q_\tau)$ quickly converges to the equilibrium profile and it is always symmetric with respect to $q_\tau = 0$.

As in Eq.(1), the *asymmetry function* $\rho_t(q_\tau) = \ln[P_t(q_\tau)/P_t(-q_\tau)]$ is commonly used to measure the asymmetry of $P(q_\tau)$ between the positive and the negative values of the fluctuations. The function $\rho_t(q_\tau)$, computed from the $P_t(q_\tau)$ shown in Fig. 3(a), is plotted in Fig 3(b). It is a linear function of its argument q_τ : $\rho_t(q_\tau) = -\Delta\beta_{t,\tau}q_\tau$. The slope $\Delta\beta_{t,\tau}$ decreases as t increases approaching the symmetric value $\Delta\beta_{t,\tau} = 0$ as $|\langle Q_{t,\tau} \rangle| \ll k_B T$. This linear relation, except for the time dependent $\Delta\beta_{t,\tau}$, is formally similar to Eq.(1), and it is the first experimental evidence of the phenomenon theoretically obtained for a relaxing spin glasses in Ref. [5]. For comparison we also plot $\rho_t(q_\tau)$ for the quench in glycerol at $t = 0$ and $\tau = 30$ s. In this case the heat exchange process is always symmetric, stressing that this is due to the nonequilibrium nature of the bath.

In absence of a theory for our experimental results we model the nonequilibrium dynamics of the particle by an overdamped Langevin equation for x :

$$\gamma_0 \dot{x}_t = -kx_t + \zeta_t, \quad \text{for } t < 200 \text{ s} \quad (3)$$

where $-kx_t$ is the harmonic force exerted by the optical trap, and ζ_t is a random noise representing the interaction of the particle with the out of equilibrium bath, *i.e.* the drop undergoing gelation. Because of the out-of-equilibrium state, the statistical properties of ζ are unknown, and it is in general a nonstationary and correlated process. Multiplying Eq. (3) by \dot{x}_t and integrating

over the time interval $[t, t + \tau]$ one obtains the energy balance Eq. (2) [14], where $Q_{t,\tau}$ is

$$Q_{t,\tau} = - \int_t^{t+\tau} \gamma_0 \dot{x}_s^2 ds + \int_t^{t+\tau} \zeta \dot{x}_s ds, \quad (4)$$

which is the sum of the viscous dissipation plus the heat injected by the bath. Notice that $Q_{t,\tau}$ cannot be estimated directly as ζ is unknown. The only experimental way to measure $Q_{t,\tau}$ is via Eq. (2).

The asymmetry of $P_t(q_\tau)$ can be directly linked to the nonstationarity of the aging bath through the quantity σ_x . Using Eq. (2) and the experimental fact that x is Gaussian [Fig. 2(b)], the analytical expression of $P_t(q_\tau)$ for large τ can be computed [11]:

$$P_t(q_\tau) = \frac{A_{t,\tau}}{\pi} K_0(B_{t,\tau}|q_\tau|) \exp\left(-\frac{\Delta_{t,\tau} A_{t,\tau}}{2} q_\tau\right), \quad (5)$$

where K_0 is the zeroth-order modified Bessel function of the second kind,

$$\Delta_{t,\tau} = \frac{\sigma_x(t)}{\sigma_x(t+\tau)} - \frac{\sigma_x(t+\tau)}{\sigma_x(t)}, \quad A_{t,\tau} = \frac{k_B T}{k\sigma_x(t)\sigma_x(t+\tau)}$$

and $B_{t,\tau} = A_{t,\tau} \sqrt{1 + \Delta_{t,\tau}^2/4}$

In Eq. (5) the asymmetry of the density is completely determined by the parameter $\Delta_{t,\tau}$ in the exponential. At equilibrium $\Delta_{t,\tau} = 0$, $A_{t,\tau} = B_{t,\tau} = 1$ regardless of t and τ , so that one recovers the symmetric equilibrium profile $P_t(q_\tau) = K_0(|q_\tau|)/\pi$ with $\langle q_{t,\tau} \rangle = 0$ [15]. In Fig. 3(a) for each experimental $P_t(q_\tau)$ we plot the theoretical prediction given by the analytical formula (5) using the respective experimental values of σ_x shown in Fig. 2(b). The excellent agreement confirms that the Langevin model (3) is suitable to describe the particle dynamics and the heat exchange with the gelatin bath after the quench.

From Eq. (5) one obtains the explicit expression for the asymmetry function $\rho_t(q_\tau) = -\Delta\beta_{t,\tau} q_\tau$ and $\Delta\beta_{t,\tau}$

$$\Delta\beta_{t,\tau} = \frac{k_B T}{k} \left[\frac{1}{\sigma_x(t+\tau)^2} - \frac{1}{\sigma_x(t)^2} \right]. \quad (6)$$

Hence, the linearity of $\rho_t(q_\tau)$ is analytically satisfied for all the values of the heat fluctuations and for all t even when $P(q_\tau)$ is strongly non-Gaussian. In Fig. 3(b) we plot the straight lines with the slope $\Delta\beta_{t,\tau}$ given by Eq. (6) and computed using the experimental values of σ_x . The good agreement with the experimental data shows that Eq. (5) verifies a fluctuation relation, as Eq. (1).

Eq.(6) gains a very intuitive interpretation if one introduces an equipartition-like relation for the particle motion for $0 \leq t \lesssim 60$ s: $k_B T_{eff}(t) = k\sigma_x(t)^2$. Here T_{eff} is the effective temperature perceived by the particle due

to its coupling with the nonequilibrium gelatin environment. In this way the parameter $\Delta\beta_{t,\tau}$ can be written conveniently as $\Delta\beta_{t,\tau} = [1/T_{eff}(t+\tau) - 1/T_{eff}(t)] T$, which is formally equivalent to that of Eq. (1). Hence $\Delta S_\tau = -k_B \Delta\beta_{t,\tau} q_{t,\tau}$ can be naturally identified as the entropy produced by the breakdown of the time-reversal symmetry due to the effective temperature imbalance at two different times after the quench. As the gelatin droplet ages ΔS_τ slows down and the particle exhibits an equilibrium-like dynamics for the experimental timescales. We point out that unlike Eq. (1) derived in Refs. [3, 4] for nonequilibrium steady states, Eq. (6) holds for a nonstationary regime created by the nonequilibrium bath.

In conclusion, we have experimentally studied the fluctuations of the heat exchanged between a trapped Brownian particle and a non-stationary bath, i.e. an aging gelatin after a very fast quench. We have shown that the distribution of the heat satisfies a fluctuation relation even when the bath is in a non-stationary state. A Langevin model justifies the observation. The analogy of our results with those obtained for spin glasses suggests that this fluctuation relation may appear as a very robust symmetry property of heat exchange processes in other kinds of relaxing systems.

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